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THERMAL TRANSFER MEASUREMENTS AT MICROWATT POWER LEVELS

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Abstract

This paper presents the design, fabrication and preliminary results for a thermal transfer standard operating at a power level of 20 µW, or less, and at temperatures below 10 K. The new converter employs a superconducting-resistive-transition edge thermometer.

Introduction

The most accurate ac voltage and current measurements are made by comparing the heating effect of the unknown ac signal to that of a known dc signal using a thermal transfer standard. These devices generally consist of one or more thermocouples arrayed along a heater resistor. Heater powers as high as a few tens of milliwatts and temperature gradients as high as 100 K are common in some thermal converters. The ultimate uncertainty for primary standards is usually limited by thermal and thermoelectric effects. To reduce these effects, a novel sensor has been developed to operate with very small temperature gradients and at cryogenic temperatures where these errors are expected to be small. This converter also offers the possibility of direct thermal transfer measurements at very low signal levels.

Superconducting Sensor Design and Fabrication

The transfer standard consists of a signal heater, trim heater, and temperature sensor all mounted on a temperature stabilized platform. The temperature of the assembly is held constant by the closed loop application of power to the trim heater. The prototype tested differs somewhat from the intended final design. In the prototype [1], the detector chip, consists of a superconducting-resistive-transition edge thermometer and a trim heater integrated on a silicon substrate. The thermometer is a Nb thin-film meander line thermally biased to operate within its superconducting-resistive transition region. The signal heater in the prototype device is a 10 Ω bifilar phosphor-bronze wire wound onto a copper bobbin. The trim heater is an 800 Ω PdAu thin-film meander line adjacent to the detector on the silicon substrate. The entire converter assembly is mounted on, but thermally isolated from, a second platform [1] which is controlled at a slightly lower temperature by another transition edge sensor and heater. The prototype sensor has a normal state resistance of 5 Ω, a critical temperature (T_c) of (9.190 ± .005) K, and a transition width of (2.90 ± .02) mK. The resulting thermometer has a sensitivity of 1800 Ω/K at its operating point.

Experiment

The superconducting sensors and experimental platform were mounted in a liquid He cryostat cooled to nearly 4 K. The resistance of the superconducting transition edge sensor on the signal stage was monitored by a commercial room temperature ac resistance bridge. The resistance bridge imbalance signal was fed to a proportional-integral-derivative controller. This controller regulated the power fed back to the trim heater to hold the sensor at a fixed resistance and hence temperature. Variations in the applied input signals (from ac to dc, for example) were observed as changes in the trim heater feedback power.

Results

To test the responsivity of the new converter, dc current was applied to the signal heater and the response of the trim heater monitored. The response of a conventional single junction thermal converter (SJTC) in series with the cryogenic converter was monitored for comparison. Fig. 1 shows that the responsivity of the cryogenic converter is substantially greater than for the SJTC over the range tested. This is primarily due to the substantial sensitivity advantage of the superconducting sensor. In addition, the cryogenic converter shows strongly enhanced response for levels approaching the maximum input power. This is expected from the electrical substitution configuration; however the utility of this effect remains to be explored. It is this excellent responsivity, as compared to conventional thermal converters, which makes the device particularly well suited for low level signals.

The ac-dc difference of the cryogenic device as a current converter was measured by the application of ac and dc input signals in a timed sequence. The current was passed through a vacuum feedthrough connector into the cryostat and then through the external room-temperature reference thermoelement (SJTC) connected in series with the signal heater. Twisted pair manganin wire was used for the signal leads inside the cryostat. From the 4 K surface to the 9 K platform, NbTi wire was used, with the intention of providing superconducting leads to the heaters to eliminate a potential source of non-equivalence error.

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However, due the proximity of the converter operating temperature to the transition temperature of the NbTi wire and the current density sustained by the heater leads, these leads may have been partially resistive. This introduced an unknown, and potentially large, error in the ac-dc difference. Even so, measurements on the first prototype device operating at about 10 μW gave an ac-dc difference at 1 kHz of (85 ± 5) μA/A.

The performance of the prototype sensor was also limited by noise in the room temperature electronics, particularly in the servo systems. In addition, the design of the sensor itself is not optimized for ac-dc difference measurements.

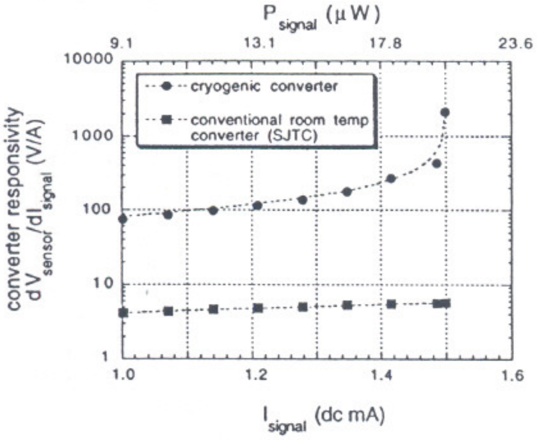

Figure 1. Responsivity graph showing the differences between the cryogenic converter and the room-temperature thermal converter (SJTC). The dashed lines are curves fits which model the expected trend in the responsivity for both types of converters.

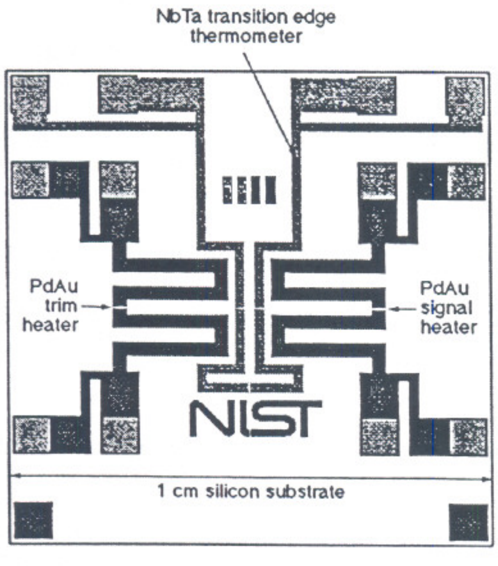

Fig. 2. New chip layout for Cryogenic Thermal Converter using superconducting resistive transition-edge thermometer and integrated thin film signal and trim heaters.

Future Plans

A new sensor (Fig. 2) is under development to address the limitations of the prototype system. Some of the improvements are:

- Replacement of Nb transition edge sensor with a NbTa alloy sensor which will reduce the transition temperature from near 9 K to closer to 5 K. This will provide three advantages; the offset power into the platform stage will be reduced as will any error due to parasitic thermal resistance within this stage, the NbTi wiring will be cooled well below its T_c at both terminations and should remain in the superconducting state during the measurements, hence eliminating a previous source of error, and the new converter will be compatible for operation in the same environment as the Josephson ac voltage source being developed at NIST-Boulder [2].
- Development and use of a thin-film signal heater. This will allow for integration of signal heater, trim heater, and sensor onto the same substrate and optimization of apportionment of power between them.
- Optimization of the experimental platform. This will include the use of NbTi superconducting leads to all sensors and heaters. The addition of a thermal shield enclosing the converter and thermally grounded to the reference platform will reduce the effects of stray radiation and help to minimize substitution power fluctuations. Efforts will also be made to reduce the noise generated by the room-temperature electronics, particularly in the servo circuits.

Conclusion

A prototype thermal converter using a superconducting transition-edge sensor has been designed and fabricated, and its ac-dc difference has been measured at a temperature of 9.1 K with a signal power of about 10 μW. Tests on this prototype indicate proof of concept, and that, with appropriate modification, this device may provide a new class of ac-dc difference standards. Operation at cryogenic temperatures may ultimately offer an improved primary standard for direct thermal transfer measurements with signal power levels of nanowatts or microwatts, and hence at much lower voltages and currents than are now possible.

References

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